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Sliding mode control of buildings with base-isolation hybrid protective system

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SUMMARY

This paper investigates the application of the sliding mode control (SMC) strategies for reducing the dynamic responses of the building structures with base-isolation hybrid protective system. It focuses on the use of reaching law method, a most attractive controller design approach of the SMC theory, for the development of control algorithms. By using the constant plus proportional rate reaching law and the power rate reaching law, two kinds of hybrid control methods are presented. The compound equation of motion of the base-isolation hybrid building structures, which is suitable for numerical analysis, has been constructed. The simulation results are obtained for an eight-storey shear building equipped with base-isolation hybrid protective system under seismic excitations. It is observed that both the constant plus proportional rate reaching law and the power rate reaching law hybrid control method presented in this paper are quite effective. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: structural control; hybrid control; base isolation; sliding mode control; reaching law method

INTRODUCTION

The vibration control schemes are roughly divided into three types, passive, active and hybrid control. As passive and active control methods have found increasing applications in civil engineering structures, the hybrid control methods, possessing the advantages of both passive and active control systems, have received considerable attention recently [1, 2]. In particular, hybrid protective systems, consisting of a combination of passive base-isolation system and active control devices, as shown in Figure 1, have been shown to be quite effective in reducing the structural responses when subjected to strong earthquakes. There are several base-isolation hybrid protective systems, such as lead-core rubber bearings and actuators, lead-core rubber bearings and variable dampers or frictional sliding bearings and actuators. In this kinds of hybrid

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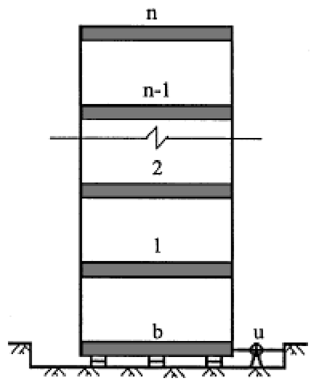

Figure 1. Building with base-isolation hybrid protective system.

control systems, the base-isolation system is used to reduce the ground motion transmitted to the building structures, whereas the active control devices are used to reduce the dynamic responses of superstructure or protect the base-isolation system from large deformation by decreasing the interstorey drift of base-isolation storey or help the base isolators to further decouple the ground motion from that of the building structures [3].

Since the dynamic behaviour of most base-isolation systems is either highly non-linear or inelastic, control of the building structures equipped with base-isolation hybrid protective system belongs to the control of non-linear structure systems. Various control methods for non-linear civil engineering structures have been investigated, including polynomial control [4, 5], acceleration control [6], instantaneous optimal control [7], dynamic linearization [8], robust control [9–11], sliding mode control [10, 12–18], neural control [19, 20], and so on. The theory of variable structure system (VSS) or sliding mode control (SMC) was proposed during the 1950s, and now has developed into a general design method for both linear and non-linear automatic control systems [21]. By using Lyapunove direct method for controller design, Yang *et al.* [10, 12–15, 18] have carried out a systematic investigation for the applications of sliding mode control to civil engineering structures.

One of the favourable features of sliding mode control is that the methods for determining switching function and designing controller may be changeable for the same control object. This paper presents a technique for designing sliding mode controller by using reaching law method [22, 23]. There are three basic types of sliding mode controller design methods including direct switching method, Lyapunove function method and reaching law method. The main advantage of using reaching law method for controller design is that the reaching law method not only establishes the reaching condition but also specifies the dynamic characteristics of the system during the reaching phase. Additional merits of this method include simplification of the solution of sliding mode controller and providing a measure for the reduction of chattering [22, 24].

In this paper, sliding mode control strategies based on the reaching law method are presented for building structures equipped with rubber bearing base-isolation hybrid protective system. Numerical simulations have been conducted for the control of a eight-storey hybrid base-isolated building with lead-core rubber bearings and actuator to investigate the performance of the presented controllers. The simulation results indicate that the hybrid control methods by using the reaching law method are quite remarkable.

EQUATION OF MOTION OF STRUCTURAL SYSTEMS

Consider a multiple-degree-of-freedom building structure equipped with rubber bearing base-isolation hybrid protective system, as shown in Figure 1. The matrix equation of motion of the structural system, subjected to a one-dimensional earthquake ground acceleration $\ddot{x}_g(t)$ and active control force $u(t)$, is given by

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = Du(t) - m\ddot{x}_g(t) \tag{1}$$

in which $x(t) = [x_n(t), \ldots, x_2(t)\ x_1(t)\ x_b(t)]^T$ are $(n+1)$ vector with $x_i(t)$ being the drift of the designated ith storey unit; $M = \mathrm{diag}[m_n, \ldots, m_2\ m_1\ m_b]$ and $m = [m_n, \ldots, m_2\ m_1\ m_b]^T$ are $(n+1) \times (n+1)$ mass matric and $(n+1)$ mass vector with m_i being the mass of the designated ith storey unit; $D = [0, \ldots, 0\ 0\ 1]^T$ is a $(n+1) \times 1$ matrix denoting that the location of the control force is at the base-isolation storey; K and C are $(n+1) \times (n+1)$ stiffness and damping matrices, respectively.

It has been demonstrated that the dynamic responses of the superstructure of base-isolated buildings generally remain in either elastic or slightly plastic status, even though under the unexpected extreme earthquakes [25]. Therefore, one can suppose that the superstructure of base-isolated buildings is of elastic. In other words, the stiffness coefficients $k_1, k_2, \ldots, k_n$ and damping coefficients $c_1, c_2, \ldots, c_n$ are supposed to be constants. While the dynamic behaviour of the base-isolation system is highly inelastic, and the stiffness coefficient k_b and damping coefficient c_b are the functions of the dynamic responses. That is, they are the functions of time t as follows:

$$k_b = k_b(t), \quad c_b = c_b(t)$$

Then, the stiffness matrix K and damping matrix C can be expressed as

$$K = \begin{bmatrix} k_n & -k_n & & & \\ -k_n & k_n + k_{n-1} & -k_{n-1} & 0 & \\ & \ddots & \ddots & \ddots & \\ & 0 & -k_2 & k_2 + k_1 & -k_1 \\ & & & -k_1 & k_1 + k_b(t) \end{bmatrix},$$

$$C = \begin{bmatrix} c_n & -c_n & & & \\ -c_n & c_n + c_{n-1} & -c_{n-1} & 0 & \\ & \ddots & \ddots & \ddots & \\ & 0 & -c_2 & c_2 + c_1 & -c_1 \\ & & & -c_1 & c_1 + c_b(t) \end{bmatrix}$$

In the state space, Equation (1) becomes

$$\dot{Z}(t) = AZ(t) + Bu(t) + E\ddot{x}_g(t) \tag{2}$$

where

$$Z(t) = \begin{bmatrix} x(t) \\ \dot{x}(t) \end{bmatrix}, \quad A = \begin{bmatrix} 0 & I_{n+1} \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ M^{-1}D \end{bmatrix}, \quad E = \begin{bmatrix} 0 \\ -M^{-1}m \end{bmatrix}$$

in which $Z(t)$ is a $(2n+2)$ state vector; A is a $(2n+2)\times(2n+2)$ non-linear system matrix; I_{n+1} is a $(n+1)\times(n+1)$ identity matrix; B and E are $(2n+2)\times 1$ matrices.

DETERMINATIONS OF SWITCHING FUNCTION

The first step of using the theory of sliding mode control for control system design is to determine the switching function. For the above-mentioned non-linear hybrid control structure system, it is necessary to convert the non-linear state equation of motion (2) by following transformation. Let the stiffness matrix K and damping matrix C be partitioned as follows:

$$K = \begin{bmatrix} K_1 \\ K_{\mathrm{b}}(t) \end{bmatrix}, \quad C = \begin{bmatrix} C_1 \\ C_{\mathrm{b}}(t) \end{bmatrix}$$

in which K_1 and C_1 are $n\times(n+1)$ sub-matrices of the stiffness matrix K and damping matrix C, respectively; $K_{\mathrm{b}}(t)$ and $C_{\mathrm{b}}(t)$ are $1\times(n+1)$ non-linear sub-matrices of the stiffness matrix K and damping matrix C, respectively. Then, the system matrix A can be expressed as follows:

$$A = \begin{bmatrix} 0 & I_{n+1} \\ -M_1K_1 & -M_1C_1 \\ -K_{\mathrm{b}}(t)/m_{\mathrm{b}} & -C_{\mathrm{b}}(t)/m_{\mathrm{b}} \end{bmatrix} = \begin{bmatrix} A_1 \\ A_{\mathrm{b}}(t) \end{bmatrix} \tag{3}$$

in which $M_1 = [(\mathrm{diag}[m_n \cdots m_2\, m_1])^{-1}\ 0]^{\mathrm{T}}$ is $(n+1)\times n$ matrix; A_1 is $(2n+1)\times(2n+2)$ sub-matrix of the system matrix A; $A_{\mathrm{b}}(t)$ is $1\times(2n+2)$ non-linear sub-matrix of the system matrix A. Substitution of (3) into Equation (2), and let

$$F_{\mathrm{b}}(t) = A_{\mathrm{b}}(t)\, Z(t)$$

to neglect the external excitation, Equation (2) can be written as

$$\dot{Z}(t) = \begin{bmatrix} A_1 Z(t) \\ F_{\mathrm{b}}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 1/m_{\mathrm{b}} \end{bmatrix} u(t) \tag{4}$$

Equation (4) is the reduced form of the non-linear control system with single control force [24]. For simplicity, the switching function can be given by the following linear form:

$$s(t) = PZ(t) \tag{5}$$

in which $P = [p_1\ p_2, \ldots, p_{2n+2}]$ is a $1\times(2n+2)$ undetermined constant matrix. It can be determined that the sliding motion on the sliding surface or switching surface, which is defined by the switching function, is stable. One can apply the following state transformation and let

$$\begin{bmatrix} \bar{Z}(t) \\ s(t) \end{bmatrix} = TZ(t) \tag{6}$$

in which $\bar{Z}(t) = [z_1(t)\, z_2(t)\ \cdots\ z_{2n+1}(t)]^{\mathrm{T}}$ is a $(2n+1)$ sub-vector of the state vector $Z(t)$; T is a transformation matrix:

$$T = \begin{bmatrix} I_{2n+1} & 0 \\ & P \end{bmatrix}$$

in which I_{2n+1} is a $(2n+1)\times(2n+1)$ identity matrix. With the transformation matrix T, the state Equation (4) becomes

$$\begin{bmatrix} \dot{\bar{Z}}(t) \\ \dot{s}(t) \end{bmatrix} = T\left\{\begin{bmatrix} A_1 Z(t) \\ F_b(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 1/m_b \end{bmatrix} u(t)\right\} \tag{7}$$

Let $p_{2n+2} = 1$ and $\bar{P} = [p_1\ p_2,\ \ldots, p_{2n+1}]$, then the transformation matrix T can be partitioned as follows:

$$T = \begin{bmatrix} I_{2n+1} & 0 \\ \bar{P} & 1 \end{bmatrix} = [T_1\ \ T_2]$$

in which T_1 is a $(2n+2)\times(2n+1)$ sub-matrix of the transformation matrix T; $T_2 = [0\ 0\ \cdots\ 1]^{\mathrm{T}}$ is a $(2n+2)\times 1$ sub-matrix of the transformation matrix T. Then, the state Equation (7) becomes

$$\begin{bmatrix} \dot{\bar{Z}}(t) \\ \dot{s}(t) \end{bmatrix} = T_1 A_1 Z(t) + T_2 F_b(t) + T_2 u(t)/m_b \tag{8}$$

Let A_1 be partitioned again as follows:

$$A_1 = [A_{11} \quad A_{12}]$$

in which A_{11} and A_{12} are a $(2n+1)\times(2n+1)$ sub-matrix and a $(2n+1)\times 1$ sub-matrix of the matrix A_1. Then, Equation (8) becomes

$$\dot{\bar{Z}}(t) = A_{11}\bar{Z}(t) + A_{12} z_{2n+2}(t) \tag{9a}$$

$$\dot{s}(t) = \bar{P}A_{11}\bar{Z}(t) + \bar{P}A_{12} z_{2n+2}(t) + F_b(t) + u(t)/m_b \tag{9b}$$

On the sliding surface, $s(t) = 0$, then one can get $z_{2n+2}(t)$ from the switching function (5), and substituting it into Equation (9a), the equation of sliding mode motion is obtained as

$$\dot{\bar{Z}}(t) = (A_{11} - A_{12}\bar{P})\bar{Z}(t) \tag{10}$$

Matrix $\bar{P}$ can be determined from (10) such that the motion on the sliding surface is stable. There are several approaches which can be used to determine the matrix $\bar{P}$, such as the pole assignment method, the linear quadratic regulator (LQR) method and the null assignment method. Finally, the switching function can be obtained as

$$s(t) = [\bar{P}\ \ 1]\, Z(t) \tag{11}$$

DESIGN OF CONTROLLERS USING REACHING LAW METHOD

In the theory of sliding mode control, the controllers are designed to drive the state trajectory into the sliding surface. To achieve this goal, the reaching law method [22, 24] is used for controller design. The reaching law is a differential equation which specifies the dynamics of the switching function. The differential equation of an asymptotically stable is itself a reaching condition. In addition, by the choice of the parameters in the differential equation, the dynamic quality of sliding mode control system in the reaching mode can be controlled. Two practical special cases of the reaching law are considered below.

(1) Consider the following constant plus proportional rate reaching law:

$$\dot{s}(t) = -\delta \operatorname{sgn}(s(t)) - gs(t) \tag{12}$$

in which δ and g are positive constants. One can derive switching function (11) with respect to time t, then substitute the equation of motion (4) into it, the following expression can be obtained:

$$\dot{s}(t) = \bar{P}A_1 Z(t) + F_{\mathrm{b}}(t) + u(t)/m_{\mathrm{b}} \tag{13}$$

Upon substituting Equation (12) into Equation (13), the closed-loop (feedback) controller based on the constant plus proportional rate reaching law is given as

$$u(t) = -m_{\mathrm{b}}\{\bar{P}A_1 Z(t) + F_{\mathrm{b}}(t) + \delta \operatorname{sgn}(s(t)) + gs(t)\} \tag{14}$$

(2) Consider the following power rate reaching law:

$$\dot{s}(t) = -\delta |s(t)|^{\alpha} \operatorname{sgn}(s(t)) \tag{15}$$

where α is a positive constant with $0 < \alpha < 1$. Upon substituting (15) into (13), the closed-loop controller based on the power rate reaching law is given as

$$u(t) = -m_{\mathrm{b}}\{\bar{P}A_1 Z(t) + F_{\mathrm{b}}(t) + \delta |s(t)|^{\alpha} \operatorname{sgn}(s(t))\} \tag{16}$$

NUMERICAL ANALYSYS OF BUILDINGS WITH BASE-ISOLATION HYBRID PROTECTIVE SYSTEM

The dynamic behaviour of the base-isolation systems is either highly non-linear or inelastic. In this study, the differential equation model presented by Wen *et al.* will be used for describing the rubber bearing base-isolation system [3, 27]. The restoring force of the base-isolation storey unit is expressed as

$$R_{\mathrm{b}}(t) = g(t) + h(t) \tag{17}$$

where

$$g(t) = c_{\mathrm{b}}\dot{x}_{\mathrm{b}}(t) + \lambda k_{\mathrm{b}} x_{\mathrm{b}}(t)$$

$$h(t) = (1 - \lambda) k_{\mathrm{b}} v_{\mathrm{b}}(t)$$

in which $x_{\mathrm{b}}(t)$ and $\dot{x}_{\mathrm{b}}(t)$ are the deformation and velocity of the base-isolation storey unit, respectively; k_{b} is the elastic stiffness; λ is the ratio of the postyielding to preyielding stiffness; c_{b} is the linear damping coefficient; $v_{\mathrm{b}}(t)$ is a variable introduced to describe hysteretic component of the deformation, with $|v_{\mathrm{b}}(t)| \leqslant 1$, where

$$\dot{v}_{\mathrm{b}}(t) = (A_y \dot{x}_{\mathrm{b}}(t) - \beta |\dot{x}_{\mathrm{b}}(t)|\, |v_{\mathrm{b}}(t)|^{nb-1} v_{\mathrm{b}}(t) - \gamma \dot{x}_{\mathrm{b}}(t) |v_{\mathrm{b}}(t)|^{nb})/d_y \tag{18}$$

in which A_y, β, γ and n_{b} are constants for governing the scale, general shape and smoothness of the hysteresis loop; d_y is the yield deformation of the base-isolation storey.

Then, one can get the representation of $F_b(t)$ as

$$F_b(t) = (R_b(t) - k_1 x_1(t) - c_1 \dot{x}_1(t))/m_b \tag{19}$$

In order to facilitate the numerical analysis, the equation of the base-isolation hybrid control structures can be expressed as

$$\dot{\tilde{Z}}(t) = f[\tilde{Z}(t)] + \tilde{B}u(t) + \tilde{e}\ddot{x}_g(t) \tag{20}$$

where

$$\tilde{Z}(t) = \begin{bmatrix} Z(t) \\ v_b(t) \end{bmatrix} \quad \tilde{B} = \begin{bmatrix} B \\ 0 \end{bmatrix} \quad \tilde{e} = \begin{bmatrix} e \\ 0 \end{bmatrix}$$

$$f[\tilde{Z}(t)] = \begin{bmatrix} A_1 Z(t) \\ (R_b(t) - k_1 x_1(t) - c_1 \dot{x}_1(t))/m_b \\ (A_y \dot{x}_b(t) - \beta |\dot{x}_b(t)| \, |v_b(t)|^{nb-1} \, v_b(t) - \gamma \dot{x}_b(t) |v_b(t)|^{nb})/d_y \end{bmatrix}$$

Equation (20) can be solved numerically using the fourth-order Runge–Kutta method as follows [26]:

$$\tilde{Z}(t) = \tilde{Z}(t - \Delta t) + \tfrac{1}{6}(B_0 + 2B_1 + 2B_2 + B_3) \tag{21}$$

where

$$B_0 = \Delta t \{ f[\tilde{Z}(t - \Delta t)] + \tilde{B}u(t - \Delta t) + \tilde{e}\ddot{x}_g(t - \Delta t)\}$$

$$B_1 = \Delta t \{ f[\tilde{Z}(t - \Delta t) + 0.5 B_0] + \tilde{B}u(t - 0.5\Delta t) + \tilde{e}\ddot{x}_g(t - 0.5\,\Delta t)\}$$

$$B_2 = \Delta t \{ f[\tilde{Z}(t - \Delta t) + 0.5 B_1] + \tilde{B}u(t - 0.5\Delta t) + \tilde{e}\ddot{x}_g(t - 0.5\,\Delta t)\}$$

$$B_3 = \Delta t \{ f[\tilde{Z}(t - \Delta t) + B_2] + \tilde{B}u(t) + \tilde{e}\ddot{x}_g(t)\}$$

in which Δt is integration time step, $\ddot{x}_g(t - 0.5\,\Delta t)$ and $u(t - 0.5\,\Delta t)$ can be obtained by the following approximate representations:

$$\ddot{x}_g(t - 0.5\,\Delta t) = 0.5(\ddot{x}_g(t - \Delta t) + \ddot{x}_g(t)) \tag{22a}$$

$$u(t - 0.5\Delta t) = 0.5(u(t - \Delta t) + u(t)) \tag{22b}$$

NUMERICAL EXAMPLES

The applications of the control methods presented in this paper are illustrated in this section. The same eight-storey building with rubber bearing isolators and actuator used in Yang *et al.* [12], as shown in Figure 2, is considered. The mass, linear stiffness and viscous damping coefficients of each floor are listed in Table I. The inelastic parameters for the base-isolation system are as follows: $d_y = 4$ cm, $\lambda = 0.6$, $A_y = 1.0$, $\beta = 0.5$, $\gamma = 0.5$, $nb = 3$. The N–S component of the 1940 El Centro earthquake record scaled to a maximum ground acceleration of 0.3 g is used as the seismic excitation, and its duration is taken to 20 s.

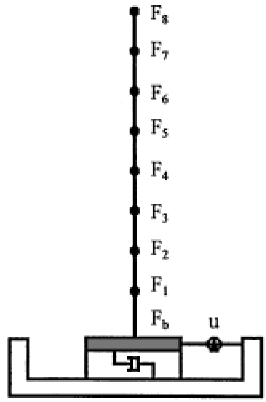

Figure 2. Structural model.

Table I. Structural parameters of the model.

Floor	F_b	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8
Mass (10^3 kg)	450	345.6	345.6	345.6	345.6	345.6	345.6	345.6	345.6
Stiffness (10^3 kN/m)	18.05	340	320	285	269	243	207	169	137
Damping (kN s/m)	26.17	490	467	410	386	349	298	243	196

Table II. Maximum response quantities of the model structure.

Floor	Base isolation $u_{max} = 0$ kN		Constant plus proportional RL $u_{max} = 1185$ kN		Power RL $u_{max} = 1243$ kN	
	x (cm)	$\ddot{x}$ (cm/s^2)	x (cm)	$\ddot{x}$ (cm/s^2)	x (cm)	$\ddot{x}$ (cm/s^2)
F_b	21.36	126	8.42	46	8.96	40
F_1	0.62	120	0.45	44	0.42	39
F_2	0.60	112	0.44	47	0.42	45
F_3	0.65	111	0.45	54	0.42	53
F_4	0.63	102	0.41	58	0.39	58
F_5	0.64	91	0.37	63	0.36	61
F_6	0.65	103	0.34	70	0.34	66
F_7	0.60	133	0.29	70	0.29	70
F_8	0.41	164	0.20	79	0.19	74

When the structure system is uncontrolled (with base-isolation only), the maximum interstorey drifts x and the maximum absolute accelerations $\ddot{x}$ of each floor are presented in Table II denoted by ‘base-isolation’.

Using the null assignment method [28] to determine the sliding surface with a parameter $\varepsilon = 1.5$, the controllers based on the constant plus proportional rate reaching law given by

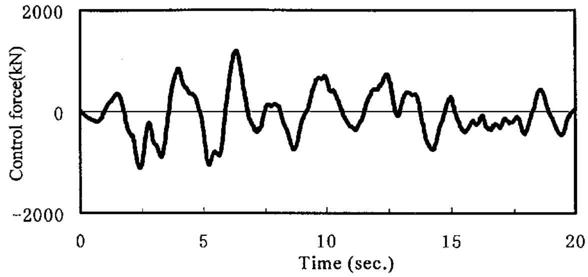

Figure 3. Control force of the constant plus proportional rate reaching law method.

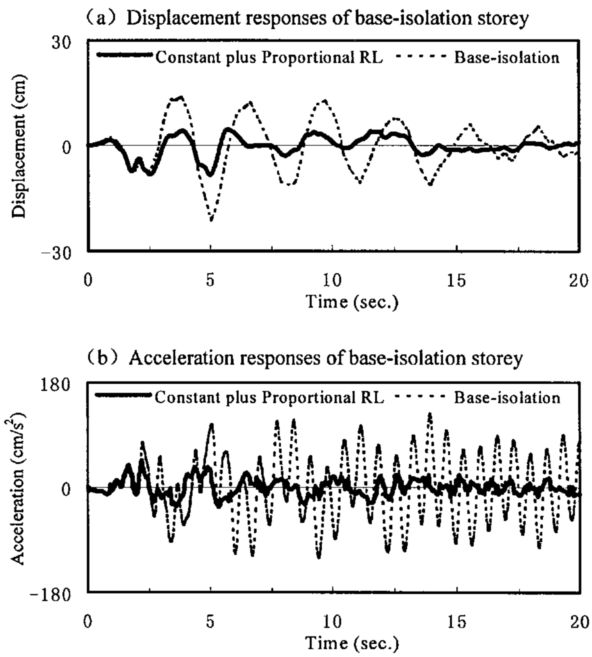

Figure 4. Comparison of responses between hybrid controlled using the constant plus proportional rate reaching law method and uncontrolled (with base-isolation only).

Equation (14) with $\delta = 0.06$, $g = 1.5$, and the power rate reaching law given by Equation (16) with $\alpha = 0.5$, $\delta = 0.75$ are used for numerical simulation. The maximum control force $u_{\max}$, maximum interstorey drifts x and absolute accelerations $\ddot{x}$ of each floor are presented in Table II denoted by 'Constant plus Proportional RL' and 'Power RL', respectively. As observed from Table II, the maximum control force $u_{\max}$ of the constant plus proportional rate reaching law method and the power rate reaching law method was 1185 and 1243 kN, respectively. The maximum interstorey drift and absolute acceleration of the base-isolation system are reduced by more than 58 per cent, while the response quantities of the superstructure are also reduced.

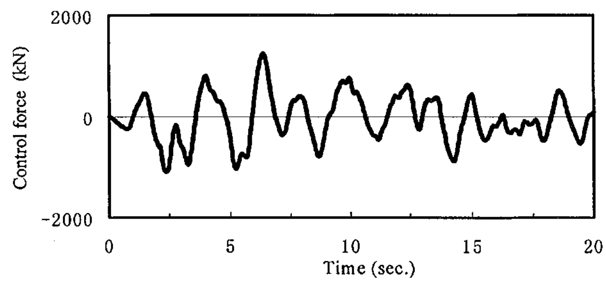

Figure 5. Control force of the power rate reaching law method.

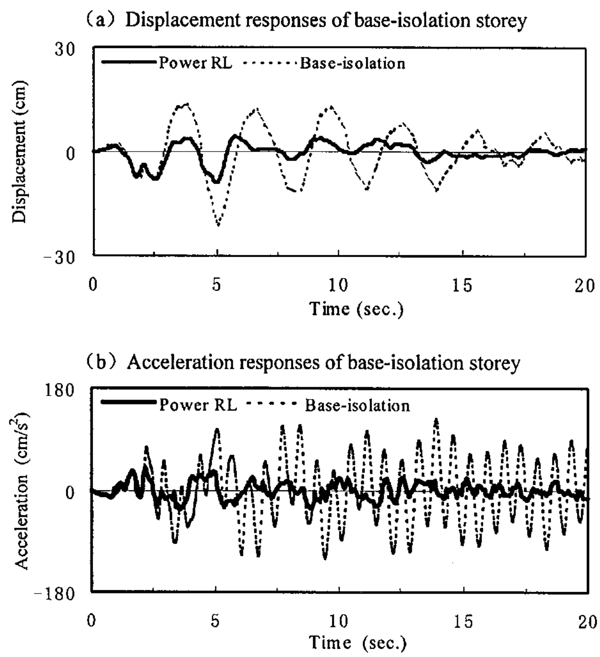

Figure 6. Comparison of responses between hybrid controlled using the power rate reaching law method and uncontrolled (with base-isolation only).

To show more detailed control performance, the control force time histories for the constant plus proportional rate reaching law method is presented in Figure 3, and the comparison of the displacement and the absolute acceleration time histories of the base-isolation storey unit between hybrid controlled (with rubber bearing isolators and actuator) using the constant plus proportional rate reaching law method and uncontrolled (with base-isolation only) are presented in Figure 4. The control force time histories for the power rate reaching law method is presented in Figure 5, and the comparison of the displacement and the absolute acceleration time histories of the base-isolation storey unit between hybrid controlled using the power rate reaching law method and uncontrolled are presented in Figure 6. From these figures, one can observe that the

both reaching law controllers are quite effective in reducing the structural responses, particularly during the peak-response period.

CONCLUDING REMARKS

In the present paper, the equation of motion of the base-isolation hybrid controlled building structures has been transformed into the reduced form of non-linear control system with single control force through some suitable simplification and conversion. Then, the determining method of switching function and the closed-loop (feedback) controllers based on the reaching law method of sliding mode control theory are proposed. By using the differential equation model presented by Wen *et al*., the compound equation of motion of the base-isolation hybrid controlled building structures, which is solved by Runge–Kutta method, has been constructed. The simulation results indicate that the sliding mode control methods presented are attractive control strategies for buildings with base-isolation hybrid protective system.

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